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POST-EARTHQUAKE SOIL CHEMICAL ANALYSIS: MECHANISMS, CHALLENGES, AND PATHWAYS FOR SUSTAINABLE RECOVERY

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ABSTRACT

Post-earthquake soil chemical analysis is critical for understanding environmental and agricultural impacts as well as public health concerns. Earthquakes often disrupt soil structures, leading to changes in pH levels, nutrient content, and the release of contaminants such as heavy metals and organic pollutants. These chemical alterations have far-reaching consequences for soil fertility, vegetation growth, and water quality. This study provides a comprehensive review of the changes in soil chemical properties caused by seismic events and highlights their implications for sustainable recovery and environmental resilience. Key mechanisms such as liquefaction, erosion, and industrial contamination are discussed, along with the effects on soil's physical and chemical stability. The paper identifies key challenges in post-earthquake soil assessments, including spatial variability of soil conditions, complex contaminant interactions, and technical limitations in testing and monitoring equipment. The absence of baseline soil data in many seismic regions further hinders accurate assessment. The study emphasizes the need for improved soil monitoring networks, international cooperation, and advancements in analytical techniques. Future research priorities are proposed, including the development of standardized methods for soil chemical assessments, exploration of sustainable remediation technologies, and integration of emerging technologies such as remote sensing and geographic information systems (GIS) to accelerate data collection. The findings underscore the importance of interdisciplinary research involving soil science, environmental health, and civil engineering to foster holistic solutions for mitigating earthquake-induced soil changes and improving post-disaster recovery strategies.

1 INTRODUCTION

Earthquakes are among the most catastrophic natural disasters, causing widespread damage to infrastructure, ecosystems, and human life. While the immediate physical destruction caused by earthquakes is well documented, the longer-term impacts, particularly on soil chemical properties, remain underexplored but are equally crucial for understanding post-earthquake recovery and resilience. Changes in soil chemistry, such as shifts in pH, nutrient content, and the release of contaminants like heavy metals and organic pollutants, can have profound effects on ecosystems, agriculture,

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Figure 1: Earthquake impact on Soil

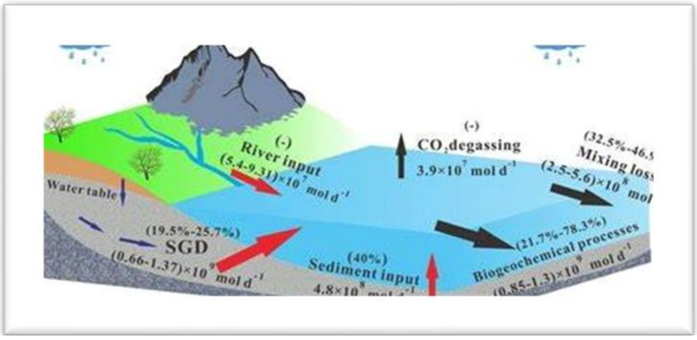
and infrastructure stability. In earthquake-prone regions, including Bangladesh, soil chemistry plays a pivotal role in maintaining ecological balance and ensuring the stability of vital infrastructure. Soil health is especially important in these areas, where agriculture is a major economic sector, and groundwater serves as a critical resource for both human and agricultural needs (Hore, 2024; Rahman & Lateh, 2017). Figure 1 shows the earthquake impact on soil.

The effects of earthquakes on soil chemistry can be categorized into immediate and long-term changes. The immediate impact often includes soil liquefaction, which alters soil texture and chemical composition, potentially releasing toxic substances into the environment (Girgin, 2011). Long-term chemical changes, such as acidification, nutrient leaching, and contamination from industrial sites, can severely affect soil fertility and agricultural productivity, complicating recovery efforts (Krausmann et al., 2011). These changes are not only a concern for agricultural regions but also for urban and industrial areas, where soil and groundwater contamination may jeopardize public health and infrastructure (Hossain et al., 2023).

Despite growing awareness of the importance of soil chemistry in earthquake resilience, there remains a significant gap in the literature, as most studies focus solely on physical impacts or soil liquefaction without considering the full spectrum of chemical changes that occur in the aftermath of seismic events (Hore et al., 2024). This is particularly critical in regions like Bangladesh, where soil is affected not only by seismic activity but also by flooding, industrial pollutants, and other environmental stressors. These chemical changes exacerbate environmental degradation and hinder the recovery of both the soil and infrastructure following an earthquake (Hore, 2024). Figure 2 shows the Carbon Cycle.

The objective of this review is to consolidate recent research on the impact of earthquakes on soil chemical properties, with a focus on the underlying mechanisms of change, environmental consequences, and implications for post-disaster recovery and risk management. By drawing on case studies from regions such as Bangladesh and Japan, this review aims to provide a comprehensive understanding of how seismic activity alters soil chemistry and the subsequent effects on soil fertility, agricultural productivity, and the design of earthquake-resistant infrastructure.

Figure 2: Carbon Cycle



2 SOIL CHEMICAL CHANGES INDUCED BY EARTHQUAKES

The relationship between earthquakes and soil chemical alterations has garnered increasing attention over the past few decades. While much of the focus has been on the physical impacts of seismic events, such as soil liquefaction, a growing body of research highlights the subtle but significant chemical changes that occur in the soil as a result of earthquakes. Understanding these chemical dynamics is crucial for evaluating post-disaster recovery and resilience strategies.

2.1 pH Variations and Nutrient Availability

Soil pH is a key determinant of nutrient availability and plays a central role in soil health. Earthquakes often trigger the release of acidic substances into the soil, causing a temporary decrease in pH levels. This acidification can disrupt the nutrient cycle, limiting the availability of essential nutrients for plants. The shaking of the ground can mobilize sulfuric compounds, which contribute to the lowering of pH, particularly in areas susceptible to liquefaction (Krausmann et al., 2011). This change in pH can also affect the solubility of metals and other toxic contaminants, further compromising soil fertility and plant health (Rahman & Lateh, 2017).

2.2 Soil Liquefaction and Its Chemical Consequences

Soil liquefaction occurs when saturated soils lose their strength and temporarily behave like liquids due to the intense shaking of the ground during an earthquake. This phenomenon can lead to significant chemical changes, including the leaching of pollutants into the surrounding environment. Liquefaction may also result in the formation of fissures in the soil, allowing hazardous substances, such as petroleum products, heavy metals, and chemicals from industrial sites, to be released into the environment (Girgin, 2011). These chemical releases pose serious environmental risks, especially in areas with industrial facilities where toxic materials are used (Hore et al., 2024).

2.3 Impact of Organic Matter on Soil Chemistry

Organic matter plays an important role in influencing soil chemistry, both during and after seismic events. Earthquakes can disrupt the breakdown of organic matter, releasing various organic acids and compounds that can alter soil chemistry (Hossain et al., 2024). Seismic activity can also lead to changes in soil moisture content, affecting the rate of organic matter decomposition. This, in turn, can influence nutrient cycling and soil fertility during the post-earthquake recovery period. The chemical compounds released from decomposing organic matter may also impact plant growth, further complicating recovery efforts (Hore, 2024).

2.4 Release of Industrial Contaminants from Seismic Activity

In regions where industrial facilities are present, earthquakes can lead to the release of hazardous chemicals into the environment. The shaking of the ground can rupture tanks, pipelines, and storage containers, causing toxic substances to spill and permeate the soil. These contaminants, including heavy metals and industrial chemicals, can significantly alter soil chemical properties, creating long-term ecological and public health risks. Several studies have emphasized the importance of developing mitigation strategies to reduce the environmental impact of industrial accidents during earthquakes, particularly in vulnerable areas (Krausmann et al., 2011; Hore et al., 2024; Hossain et al., 2023).

3 CHEMICAL ANALYSIS OF SOIL POST-EARTHQUAKE

After a seismic event, the chemical properties of soil undergo significant changes that can have long-term implications for both the environment and human health. Soil, as a dynamic natural resource, is influenced by a range of factors during and after an earthquake. These changes include alterations in pH, nutrient availability, heavy metal contamination, and shifts in organic matter composition (Girgin, 2011; Hossain et al., 2023). The process of chemical analysis of soil post-earthquake is critical in understanding the extent of damage, mitigating risks associated with contamination, and formulating recovery strategies for agriculture, public health, and infrastructure. This section explores the key chemical parameters that are commonly assessed in post-earthquake soil analysis, methodologies used in these assessments, and the implications of the findings for recovery efforts. Figure 3 shows the ground and soil failure after earthquake at Ranau, Sabah.

Figure 3: Ground and soil failure after earthquake at Ranau, Sabah (Foong, 2016)

3.1 Key Chemical Parameters Assessed in Post-Earthquake Soil Analysis

Post-earthquake soil analysis focuses on several key chemical parameters that are vital for understanding the environmental impacts of seismic events. These parameters provide critical insights into soil health and guide recovery efforts for both agriculture and public health.

3.1.1 Soil pH

Soil pH is a fundamental indicator of soil health, reflecting its acidity or alkalinity, which directly influences nutrient availability and microbial activity. Earthquakes can induce changes in pH levels due to soil liquefaction, which enhances the mobility of both acidic and alkaline contaminants (Krausmann et al., 2011). In regions affected by acid rain or industrial activity, post-earthquake acidification may intensify, potentially reducing soil fertility and increasing the leaching of heavy metals. On the other hand, alkaline conditions can hinder nutrient uptake by plants, complicating agricultural recovery (Hore, 2024). Therefore, monitoring pH fluctuations is essential for assessing risks to agriculture and human health in the aftermath of an earthquake.

3.1.2 Nutrient Leaching and Availability

Seismic events such as landslides, soil liquefaction, and flooding can trigger the redistribution and mobilization of key nutrients like nitrogen, phosphorus, and potassium, which are crucial for plant growth. These shifts can negatively impact soil fertility and agricultural productivity (Young et al., 2004). For example, liquefaction and flooding often result in increased surface runoff, which accelerates nutrient leaching, further depleting soil nutrient levels (Steinberg et al., 2001). Comprehensive chemical analysis of both macro- and micronutrients, such as zinc, copper, and manganese, is critical for evaluating post-earthquake soil health and developing appropriate fertilization strategies for recovery.

3.1.3 Heavy Metals and Toxic Contaminants

Earthquakes can mobilize toxic chemicals and heavy metals from industrial sites, hazardous waste storage, and mining areas into the surrounding soil, posing significant environmental and public health risks. Substances such as lead, arsenic, cadmium, and mercury may be released into the soil after seismic events (Cruz et al., 2004). In industrial zones, post-earthquake soil chemical analysis often prioritizes the detection and quantification of these hazardous pollutants, which are harmful to ecosystems, plant life, and human populations. Additionally, these contaminants can infiltrate groundwater, compounding the health risks and necessitating urgent interventions (Hore et al., 2024).

3.1.4 Organic Matter Degradation

Organic matter is a vital component of soil that supports structure, water retention, and nutrient cycling. Earthquakes can disrupt the integrity of soil structure, leading to the loss of organic matter or alterations in its composition (Hossain et al., 2023). The physical displacement of soil particles may expose organic material to oxygen, speeding up decomposition processes. Alternatively, in areas where soil becomes waterlogged due to liquefaction, anaerobic conditions can prevail, resulting in the production of harmful gases such as methane and hydrogen sulfide. Analyzing organic matter content provides valuable information for assessing soil fertility and identifying strategies for restoring soil health in the aftermath of an earthquake.

3.2 Methodologies for Soil Chemical Analysis Post-Earthquake

To effectively assess soil conditions after an earthquake, several methodological approaches are employed. These methods involve multiple stages: sample collection, preparation, chemical analysis, and data interpretation. The selection of techniques depends on the specific objectives of the analysis, the type of contamination, and available resources.

3.2.1 Soil Sampling

Systematic soil sampling is essential for capturing the spatial variability of soil chemical properties across areas affected by earthquakes. Samples are typically collected from varying depths and locations, especially from regions susceptible to liquefaction, landslides, or flooding (Hore et al., 2024). Sampling should be conducted immediately following the earthquake and then periodically throughout the recovery process to monitor changes over time.

3.2.2 Spectroscopic Techniques

Spectroscopic methods, including Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS), are commonly used to detect and quantify heavy metals and other toxic substances in soil (Hossain et al., 2023). These methods offer high sensitivity and precision, allowing for the identification of trace elements that may pose significant environmental and health risks.

3.2.3 Chromatographic Techniques

Gas Chromatography (GC) and High-Performance Liquid Chromatography (HPLC) are frequently employed to analyze organic compounds and pollutants in soil samples. These techniques are particularly effective for identifying petroleum hydrocarbons, pesticides, and other organic pollutants that may be released due to infrastructure damage following an earthquake (Steinberg et al., 2001).

3.2.4 Soil pH and Nutrient Analysis

Soil pH is typically measured using a potentiometer, while nutrient levels are analyzed through techniques like the Mehlich-3 extraction method, which evaluates both macronutrients and micronutrients. These analyses are invaluable for understanding changes in soil fertility and nutrient availability after a seismic event.

4 ANALYSIS AND DISCUSSION

The chemical properties of soil undergo significant changes following an earthquake, which can have long-lasting effects on the environment, public health, and economic recovery—especially in agriculture and infrastructure. This section synthesizes key findings from the review of post-earthquake soil chemical analysis, comparing them to previous research, and discusses the implications for recovery efforts, as well as the challenges inherent in conducting soil analysis in disaster-affected regions.

4.1 Agricultural Recovery Post-Earthquake: The Role of Soil Chemistry

Agriculture is often one of the most affected sectors following a major seismic event, and the changes in soil chemistry play a critical role in determining the success of long-term recovery. The leaching of essential nutrients such as nitrogen and potassium, as well as contamination by heavy metals and toxic chemicals, can significantly reduce soil fertility and hinder crop productivity (Krausmann et al., 2011; Girgin, 2011). For example, changes in soil pH after an earthquake can affect nutrient uptake, particularly in crops that are sensitive to changes in soil acidity or alkalinity (Hore, 2024).

Research by Hossain et al. (2023) highlights that one of the most significant challenges in agricultural recovery is the loss of soil fertility caused by nutrient leaching and contamination from industrial activities, which are often exacerbated by soil liquefaction and flooding. Soil chemical analysis is vital for identifying nutrient deficiencies, guiding fertilization practices, and preventing the cultivation of crops that may accumulate toxic heavy metals. For example, high concentrations of arsenic and cadmium in soils after the 1999 Turkey earthquake (Steinberg et al., 2001) underscore the need for soil remediation strategies, including phytoremediation and soil amendments.

The agricultural recovery process, however, may be slow, and sustained monitoring is required. Long-term soil degradation necessitates not only immediate interventions but also strategies for sustainable land management. It is also important to consider how changes in soil chemistry interact with physical soil properties, such as texture and structure, which influence water retention and root growth—critical factors for crop recovery (Rahman & Lateh, 2017).

4.2 Environmental and Health Risks from Soil Contamination

Beyond agriculture, soil contamination after an earthquake poses significant environmental and public health risks. Earthquakes can lead to industrial spills, the release of hazardous chemicals from damaged infrastructure, and the mobilization of toxic elements due to liquefaction. This can lead to contamination of both soil and groundwater (Cruz et al., 2004). The review emphasizes cases such as the 2004 Indian Ocean tsunami and the 1999 Turkish earthquake, where high levels of heavy metals such as lead, mercury, and cadmium were detected in soils. These contaminants are persistent and pose long-term health risks, particularly to communities relying on groundwater for drinking and irrigation (Iqbal et al., 2012).

Soil chemical analysis is crucial for assessing these environmental risks and formulating public health strategies. Early detection of toxic substances allows for timely intervention, such as the isolation of contaminated areas, the introduction of phytoremediation plants, or the treatment of polluted groundwater (Hossain et al., 2023). Additionally, soil testing helps public health authorities assess the extent of exposure to harmful materials and implement protective measures for local communities.

For instance, the Fukushima accident (Hasegawa et al., 2016) and similar events demonstrate the importance of prompt soil chemical analysis to identify and mitigate contamination risks. Toxic substances can move rapidly through soils, making it crucial to act quickly to prevent long-term health issues, such as cancer, neurological disorders, and developmental problems in children (Steinberg et al., 2001). Thus, post-earthquake soil chemical analysis not only supports immediate disaster response but also aids in planning for long-term recovery and health monitoring.

4.3 Challenges in Post-Earthquake Soil Chemical Analysis

While soil chemical analysis is an essential tool for post-earthquake recovery, several challenges complicate its application. One of the main challenges is the high degree of variability in soil properties and the impact of seismic events on soil chemistry. Changes in soil composition can be highly localized, depending on factors such as soil type, earthquake intensity, and proximity to industrial sites or contamination sources (Krausmann et al., 2011). This spatial variability necessitates careful sampling strategies and the use of advanced analytical techniques to ensure comprehensive and accurate results.

The presence of multiple contaminants—such as heavy metals, petroleum hydrocarbons, and agricultural chemicals—further complicates soil analysis. These substances may interact, leading to complex chemical reactions that can alter their mobility and toxicity (Hore et al., 2024). Additionally, many earthquake-prone regions lack baseline data on soil chemistry, which makes it difficult to assess the extent of changes caused by seismic activity (Hossain et al., 2023). Establishing baseline soil data and improving soil monitoring networks in these regions is critical for effective post-disaster recovery.

Moreover, technical and financial constraints present significant barriers to comprehensive soil analysis in disaster zones. Specialized equipment and trained personnel are required for accurate testing, particularly when analyzing trace elements and organic contaminants. In the aftermath of an earthquake, these resources may be limited. Overcoming these challenges will require international cooperation, capacity building, and investment in infrastructure to ensure the timely and effective implementation of soil chemical analysis in the aftermath of earthquakes.

5 CONCLUSION

Soil chemical analysis is crucial for understanding the environmental, agricultural, and public health impacts of earthquakes. This review has highlighted how seismic events, through processes like liquefaction, erosion, and industrial contamination, significantly alter soil properties. By examining soil pH, nutrient levels, and the presence of hazardous contaminants, soil chemical analysis offers essential insights for guiding post-earthquake recovery.

Key findings emphasize the importance of prompt, comprehensive soil testing in earthquake-affected areas. Soil fertility is often diminished due to nutrient leaching, and contamination from hazardous chemicals can have long-term consequences for ecosystems and human health. The agricultural sector, in particular, faces significant challenges in restoring soil health, as changes in soil chemistry disrupt crop growth. Early detection of these changes is critical for applying appropriate remediation measures, including fertilization, soil amendments, and phytoremediation. Additionally, the review stresses the broader environmental and health risks posed by toxic substances in the soil, which can persist and threaten public safety. Despite its importance, several challenges remain, including the spatial variability of soil changes, complex interactions between contaminants, and limited technical resources in disaster zones. Addressing these requires improved soil monitoring, baseline data, and enhanced technical capacity in affected regions.

Looking forward, future research should refine methodologies for soil analysis, explore advanced remediation techniques, and incorporate emerging technologies, like remote sensing and soil sensors, to accelerate recovery efforts. Soil chemical analysis remains indispensable for post-earthquake recovery, and continued advancements will ensure more effective responses to future seismic events.

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